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WEAPONS SYSTEMS RESEARCH LABORATORY

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SOUTH AUSTRALIA

TECHNICAL REPORT
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A SOLID PROPELLANT CHARGE DESIGN WITH NEGATIVE EFFECTIVE PRESSURE EXPONENT USING FORCED CONE BURNING

R D. IRVINE and P.C. WINCH

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A SOLID PROPELLANT CHARGE DESIGN WITH NEGATIVE EFFECTIVE PRESSURE EXPONENT USING FORCED CONE BURNING

R.D. Irvine and P.C. Winch

SUMMARY

A novel method of making a solid propellant rocket motor or gas generator charge with a negative effective burning rate pressure exponent (negative dr_b/dP) is presented. The negative exponent characteristic can be obtained independently of burning rate and other bulk propellant properties (specific impulse, flame temperature, signature, mechanical properties, etc) which can be chosen as required.

The charge is constructed with a core, (or several cores), of propellant with an intrinsically negative pressure exponent with the bulk of the charge made up of any propellant with a lower burning rate than the core propellant over the pressure range of interest. The core propellant burning rate range can be adjusted to give the desired value by a method of burning rate acceleration.

Suitable core materials and burning rate acceleration methods are reported, and the use of such a charge in a rocket motor or gas generator with a variable area nozzle to give controllable thrust is discussed.

POSTAL ADDRESS: Director, Weapons Systems Research Laboratory,
Box 2151, GPO, Adelaide, South Australia, 5001.

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cylindrical matrix has a diameter D and is inhibited from burning on all faces except the end face. The single core charge is illustrated in figure 1. If for any pressure, the bulk burning rate r_b is greater than the core burning rate r_{bc}, then the charge burns with a planar surface and is of no interest. Therefore consideration is restricted to the pressure range where $r_b \leq r_{bc}$.

If r_{bc} is greater than r_b, the surface will transform from a flat surface, to a concave cone of semi-angle θ, which is the equilibrium surface for the geometry. Thereafter, the surface regresses with a constant cone angle θ, which is a fuction only of the ratio of the burning rates, (equation (2)).

The quasi steady burning surface area is

$$A_b = \pi D^2/4\sin\theta \tag{3}$$

The volume of propellant consumed per unit time is

$$\begin{aligned} dV/dt &= A_b r_b \\ &= \pi D^2 r_b/4\sin\theta \\ &= \pi D^2\ r_{bc}/4 \end{aligned} \tag{4}$$

Equation (4) shows that the volume of propellant consumed per unit time is the same as the original flat surface would consume if it were burning at the accelerated burning rate r_{bc}, rather than r_b. Thus the charge produces gas at a rate which is determined by the core burning rate, but the nature of the gas produced is that of the bulk propellant. If the core propellant burns with a negative burning rate pressure exponent, the entire charge produces gas at a rate which is determined by that negative pressure exponent characteristic.

Designers of controllable rocket motors or gas generators are interested not only in the steady state performance given above, but also in the ability to move from one steady state to another, and in particular, in the transition time required for the motor to respond to a change in the control.

For simplicity of calculation, development of the burning surface is assumed to take place at constant pressure. This could be achieved for example using a variable nozzle to give a constant ratio of nozzle area to propellant area. Then if pressure is constant, the cone angle being formed, $\theta = \sin^{-1}(r_b/r_{bc})$ will be constant during the transition. Winch and Irvine(ref.6) have calculated the transition times in units of $D/2r_b$, the time taken to burn from the centre of the cylinder to the edge and it was shown that the time taken to burn from one cone to another is always at least $D/2r_b$, but for cones steeper than 45°, the time is never greater than $\sqrt{2}(D/2r_b)$.

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charge geometry and motor thrust requirements. It has been shown(ref.6) that the worst case transition time within the above burning rate range is minimised by choosing r_b, the bulk propellant burning rate, so that the minimum cone angle θ_{min} equals 45° or $r_b = r_{bcmin}/\sqrt{2}$. The maximum transition time is then,

$$\tau = \sqrt{2}(D/2r_b)$$

$$= D/r_{bcmin}$$

3. CHARGE BURNING CHARACTERISTICS WITH INFINITE NEGATIVE EXPONENT PROPELLANT CORE

The limit of negative exponent is a step decrease in burning rate as the pressure rises over a vanishingly small pressure range. The important parameter is the magnitude of the change in burning rate, expressed as the ratio of r_{bcmax} to r_{bcmin}. Cohen, Landers and Lou(ref.1) refer to this ratio as the turn-down ratio. A charge whose effective burning rate is controlled by a central core of such negative exponent propellant will, at equilibrium, burn at a constant pressure, regardless of nozzle area, over a limited range of nozzle areas.

Suppose, for example, that at pressure P_o, the core had a negative exponent which approaches infinity, $n \to -\infty$, and some finite burning rate $r_{bc}(P_o)$.

Then, for P sufficiently near P_o, equation (1) becomes

$$r_{bc} = r_{bc}(P_o) \cdot (P/P_o)^n \tag{5}$$

The usual motor ballistic formulae give

$$\rho_p A_b r_b = PA_t/c^* \tag{6}$$

where A_b is the propellant area, A_t the nozzle throat area, and c^* the characteristic exhaust velocity of the propellant. At equilibrium, A_b is constant, equal to $\pi D^2 r_{bc}/4r_b$ and hence

$$P = P_o(\rho_p c^* \pi D^2 r_{bc}(P_o)/4A_t P_o)^{1/(1-n)} \tag{7}$$

As n tends to $-\infty$, P tends to P_o for all A_t. The burning rate is still given by equation (6)

$$r_{bc} = 4P_o A_t/\pi\rho D^2 c^* \tag{8}$$

The variable nozzle area must be appropriate for the burning rate range r_{bcmax} to r_{bcmin}, but within that range the motor will find an equilibrium burning rate and an equilibrium surface area to match the nozzle.

In this sense, a negative exponent charge with infinite exponent is identical to a constant pressure source. The chamber pressure is constant, independant of the nozzle area, while the mass flow is directly proportional to the nozzle area.

A charge with a central core of negative exponent propellant and a bulk of slower burning propellant of different properties, will have an effective burning rate at equilibrium equal to that of the negative exponent propellant, and gas properties of the bulk propellant. The time to reach equilibrium can be kept to less than D/r_{bcmin}, as shown in reference 6 where D is the diameter of the grain and r_{bcmin} is the minimum burn rate of the core. This transition time, τ, to reach equilibrium will be a limiting feature of the charge performance. Although a new dimension is added to the performance and flexibility of charge design, it comes with the penalty of transitions which require finite times to complete. This may well conflict with controllability requirements. The transition time can be reduced by reducing the charge diameter, or increasing the minimum core burning rate. There are systems limitations on charge diameter and, with only a few negative exponent propellants available, particular core burning rates may not be available.

4. MULTIPLE CORE CHARGES

The transition time can also be reduced by incorporating many cores of negative exponent propellant. equally spaced across the grain. Winch and Irvine have discussed the use of multiple cores for forced cone burning to minimise the transition time and their results are quoted in reference 6. For multiple cores, the worst case transition time becomes Z/r_{bcmin} where Z is approximately the distance between cores. If the cores are optimally spaced, Z is approximately equal to $D/\sqrt{N}$ where N is the number of cores. The transition time was shown to be:

$$\tau = D/r_{bcmin}\sqrt{N} \tag{9}$$

The significant parameter needed for active control is the ratio of the transition time τ to the maximum duration of firing t_f.

$$t_f = L/r_{bcmin}$$

where L is the length of the charge. Hence

$$\tau/t_f = D/L\sqrt{N} \tag{10}$$

Table 1 lists the ratio τ/t_f for various L/D ratios and various numbers of cores, N. It can be seen, for instance, that to achieve a value of τ/t_f of less than 0.05 requires an L/D greater than 4, with N greater than 20, while a τ/t_f of less than 0.01 needs high values of L/D, greater than 8, and more than 100 cores.

TABLE 1. TRANSITION TIME/BURN TIME RATIO FOR VARIOUS LENGTH TO DIAMETER RATIOS AND NUMBERS OF CORES

	N				
L/D	1	4	20	50	200
1	1.0	0.5	0.223	0.141	0.071
2	0.5	0.25	0.112	0.071	0.035
4	0.25	0.125	0.056	0.035	0.018
8	0.125	0.062	0.028	0.018	0.009
16	0.062	0.031	0.014	0.009	0.004

Reference 6 also discusses the useful lower limit to τ/t_f given by the time constant of the volume of the rocket motor case. There is little value in reducing the transition time to less than the order of this volumetric time constant, τ_m. If the charge L/D ratio, and the number of cores are sufficiently large that $\tau \leq \tau_m$, then the charge made using negative exponent core technology will have a thrust response determined by the response time of the chamber volume to a change in nozzle area.

5. NEGATIVE EXPONENT PROPELLANTS SUITABLE FOR CORE MATERIAL

5.1 Previous negative exponent propellants

Cohen, Landers and Lou(ref.1) report a family of cast composite ammonium perchlorate based propellants, with negative exponents. The significant parameters quoted are the exponent n and the turn-down ratio r_{bmax}/r_{bmin}. The propellants quoted vary from cool propellants for gas generator applications with n of -2.7, and a turn-down ratio of 2, through moderate specific impulse propellants with n of -1.0 and turn-down ratio of 2.6, to high specific impulse aluminised propellants with n of -0.5 and turn-down ratio of 1.5. The minimum burning rate for the gas generator propellant was 1.5 mm/s, while for the higher specific impulse propellants, r_{bmin} was about 5 to 6 mm/s. Typical variation of r_b with P is shown in figure 2.

It has been well known for many years that double base propellants can be modified to give "plateau" (n=0) and "mesa" (n≤0) burning over a limited pressure range. Usually the turn-down ratio is quite small, and n is very close to zero over a wide pressure range, but extreme cases are occasionally reported(ref.7).

5.2 Extruded double base propellants produced at Weapons Systems Research Laboratory (WSRL)

A survey of experimental Cast Double Base (CDB) and Extruded Double Base (EDB) propellants made at Propulsion and Ballistics Division of WSRL at Salisbury, South Australia over many years yielded the extruded double base propellant with burning rate dependence on pressure shown in figure 3(ref.8). This propellant formulation has the following desirable properties:

(i) Turn-down ratio of 2.06.

(ii) Average n over the range r_{bmax} to r_{bmin} of -2.7.

(iii) Peak n of about -7.

(iv) Minimum burn rate in negative n region of 5.0 mm/s.

(v) Very good batch-to-batch and strand-to-strand repeatability.

(vi) Easily producible in strand form.

(vii) Compatible with a wide range of CDB propellants.

The maximum and minimum burning rates of this propellant of 10.3 mm/s at 5.5 MPa and 5 mm/s at 7.5 MPa lie in a reasonably useful range, being fairly typical of burning rates used in long burning time end-burning motors.

The turn-down of this propellant is particularly sudden, with the drop in burning rate occurring over such a narrow range of pressure that the strand-burning equipment was unable to hold pressure to a sufficient accuracy to measure the real exponent. The drop from 7 to 8 mm/s at 7 MPa to 5 mm/s at 7.25 MPa is the limit of resolution of WSRL equipment.

The propellant has been extruded in 6 mm, 3 mm and 1 mm diameter strands without difficulty, and no variation in burning rate characteristics has been observed with change in diameter. Strands of the propellant have been incorporated into small CDB charges to investigate this means of charge manufacture. The small charges were statically fired and the conical surfaces on interruption as shown in figure 4 conformed to the burning rate determined by the strands.

Two areas of performance have room for improvement. The size of the turn-down ratio (2.06) is useful, but a propellant having a significantly larger value would greatly increase the usefulness. The burning rate range of 5 to 10 mm/s is useful, but bulk propellants with burning rates lower than 5 mm/s typically also have low specific impulses. If the core propellant burning rate were increased to 10 to 20 mm/s, it would enable the use of the large number of higher energy CDB propellants with burning rates of 5 to 10 mm/s at 7 MPa. Even higher core burning rates would be useful for some applications.

5.3 Accelerated burning of core material

Winch and Irvine(ref.6) have reviewed a wide range of means of inducing accelerated burning rate in an end-burning charge by forced cone burning. By considering the negative exponent core strand alone, the same ideas of forced cone burning can be carried over to increasing the core burning rate. If the core strand had, for example, a central wire core the thermal feedback from the flame-zone would increase the burning rate of the core strand.

Of course, not all mechanisms for amplifying the burning rate will be useful. If the amplification is a positive function of pressure, or if the amplification is greatest when the basic burning rate is least, then the increase in the burning rate comes only at the cost of both the size of the turn-down ratio, and the negative exponent. Figure 5 shows the effect of the inclusion of copper wires of 0.25 mm diameter on the burning rate pressure dependence of the negative exponent EDB propellant described in Section 5.2. It can be seen that although the burning rate is increased significantly, the turn-down ratio has been eliminated altogether. A better understanding of the mechanism of negative exponent propellants may

be gained by studying the effect of increased heat feed-back by this means. This in turn might enable the selection of appropriate means of burning rate amplification.

One means of amplifying the burning rate that is independent of pressure and burning mechanism is the use of Bradfield cavities. Bradfield(ref.5) has shown that if a spaced line of cavities is included in a charge, then the average burning rate of the line is amplified by the simple geometrical ratio of the pitch spacing of the cavities, P, to the length of the propellant between them, S.

$$(r_{bc}/r_b)_{average} = P/S \tag{11}$$

This is shown in figure 6. The resultant accelerated mean burning rate causes an approximate cone to form in the charge. Of course, the pulsed nature of the cavity line leads to a fluctuating slope on the conical surface, but Bradfield has shown that the resultant surface area fluctuations are small if the spacing of the cavities is small compared to the charge radius. The use of a number of cavity lines, especially out of phase with each other, decreases any fluctuations still further.

If the EDB negative exponent propellant core incorporates Bradfield cavities then the burning rate, at both r_{bcmax} and r_{bcmin}, would be increased by the ratio of cavity pitch to propellant length between cavities, P/S. The negative exponent and the turn-down ratio would remain unaffected. This is because the propellant still burns with the negative exponent characteristic, but occasionally the flame-front jumps, with almost no time delay, the distance through the cavity. Thus a distance P is burnt in the time taken to burn a distance of S in the propellant.

Figure 7 shows a suggested negative exponent strand made using Bradfield cavities, to double the burning rate of the EDB propellant to a range 10 mm/s to 20 mm/s. Each strand is constructed of a large number of small cylinders, alternating solid and hollow, of equal length and extruded from the same negative exponent propellant, and glued together with an appropriate solvent adhesive. Any amplification is possible by using different lengths of hollow and solid cylinders. Figure 8 shows a multi-core charge with a core burning rate of 10 mm/s to 20 mm/s, a bulk burning rate of 8 mm/s and a transition time from one burning surface area to another of 0.01 t_b, where t_b is the time of burn at the lower rate.

In practice, any method which rapidly moves the flame a distance of P-S produces the desired effect of increasing the burning rate without affecting the core pressure exponent or turn-down ratio. For instance, the incorporation of "Pyrofuse" Al-Pd exothermic alloying fuse wire, which burns at least ten times as fast as the EDB formulation, in the form of short lengths regularly or randomly spaced, might be expected to amplify the burn rate by the ratio (L+G)/G where L is the effective axial length of the "Pyrofuse", and G the mean gap between lengths. In practice, test results were not promising, and it is believed that a finite and significant time is taken to heat the wires to ignition. The amplified burning rate of negative exponent propellant with pyrofuse staples is shown in figure 9.

6. DISCUSSION AND APPLICATIONS

The charge illustrated in figure 8 has combined several very useful properties. Firstly, it has a large negative exponent and therefore can be used as a controllable gas generator or thrust source with little variation in chamber pressure. Secondly, the actual burning rate range can be adjusted to give a useful mass flow rate for a particular application. Thirdly, and without losing the other two characteristics, the bulk propellant can be chosen from a wide range of available propellant formulations to give particular requirements, such as high impulse (aluminised CDB, for example), low smoke (non-aluminised CDB), or low flame temperature, which would vary from application to application.

In a variable area nozzle controlled mass flow rocket motor or gas generator the burning rate must be a strong function of pressure for any variation of thrust with nozzle area to occur. In the past, high positive exponents, $0.5<n<1$, have been used but they have the disadvantage that small changes in nozzle area cause large changes in pressure. Thus the motor case must be designed for much higher pressures than the mean pressure. A further disadvantage is that response is slow, with a decrease in nozzle area leading to a decrease in thrust initially, followed then by an increase in thrust after the chamber reaches the new pressure.

Cohen, Landers and Lou(ref.1) proposed and demonstrated that using a negative exponent propellant charge with a variable area nozzle gives a much narrower range of chamber pressures, which optimises motor case design, as well as giving much better control response rate. Control response rate is improved because opening the nozzle instantly gives more thrust, and this is followed by an increase in burning rate to sustain the higher level of thrust with a higher rate of gas production.

The negative exponent cored charge described in this report has most of the advantages of a charge made entirely of negative exponent propellant. The pressure remains nearly constant, and thus the motor chamber and nozzle can be designed around that constant pressure, with only a small safety factor. However, the speed of control does not reach the very rapid response of the pure negative exponent charge and so the control of thrust with the variable nozzle must be considered fully to ensure stable operation. The response can be made faster than the positive exponent alternative, which is slowed down by the need to fill the chamber to a considerably different pressure. The control of cored charges with pintle nozzles needs to be considered separately, in greater depth.

The burning rate range over which such a charge can be operated is extremely wide. Bradfield(ref.5) has demonstrated amplifications of 6, and factors of 10 seem reasonably practical. This could give charge burning rates up to 100 mm/s, if required. The lower limit of burning rate with the negative exponent propellant reported here is 5 mm/s, but Cohen, Landers and Lou(ref.1) report a cast composite propellant with a turn-down ratio of over 2 and a minimum burning rate of 1.5 mm/s. Thus the means are available to make negative exponent cored charges with turn-down ratios of at least 2, over a range of minimum burning rates of 1.5 mm/s to at least 50 mm/s.

A turn-down ratio of 2 is useful for many applications. However, there is scope for improvement in this area. Recognition of the value of high turn-down ratios, combined with an investigation into the factors leading to them, is needed to lead to a more directed search for suitable propellants. The highest value reported by Cohen, Landers and Lou is 2.6, with a non-aluminised cast composite propellant, with minimum burning rate of 4.5 mm/s and average exponent of -1.0.

The great advantage of the negative exponent cored charge described here is the separation of the ballistics of charge design for controlled nozzle solid propellant motors into three separate areas:

(a) The negative exponent core material

(b) The burning rate of the core

(c) The bulk properties of the charge

Each area can be independantly optimised, so that the resultant charge is no longer such a compromise, and the range of propellants available to the designer is increased enormously.

Initially a designer would select a propellant for the core to have a suitably high negative exponent, and turn-down ratio. Values of n of less than -2.5 have been produced in EDB stands, with a turn-down ratio of greater than 2. Cast composite propellants are also available, with n less than -1.0 and turn-down ratios greater than 2.0 (and up to 2.6).

The designer, having selected the core propellant, can then choose an accelerator (such as Bradfield cavities, or similar devices that cause the flame-front to progress very rapidly through a fixed fraction of the propellant) to raise the burning rate range of the core propellant to the range required by the application.

Finally, the designer is free to choose the bulk propellant from any of the wide range of available propellants with suitable propellant compatibility with the core propellant. A minimum bulk burning rate of a third of the minimum core burning rate up to a maximum equal to the minimum core burning rate would probably be acceptable. The designer can design the bulk for maximum specific impulse, low plume signature, maximum volumetric specific impulse, low cost or other properties, while ignoring pressure exponent (except to avoid values near unity for safety reasons) and temperature coefficient.

Gas generators for pneumatic actuators are an application where controllability is the most important feature. Rapid response rate, and the ability to choose low flame temperature propellants are particularly attractive.

Such a charge could also be used in gas generator fuelled ram-jets or ducted rockets. In this application, a very fuel rich propellant is burnt in a chamber, exhausted into a duct where it is mixed with air, and the resultant mixture is burnt and exhausted as a ram-jet. The control is used to give varying mass flow to compensate for varying air flow at different flight conditions. In this application, speed of response can be quite slow and turn-down ratios of 2 may be adequate, but the ability to choose a very fuel rich propellant without compromising pressure exponent or burning rate is extremely important.

Australia has been active in the hovering rocket area which imposes a need for varying thrust rocket motors. Conventional controllable rocket motors pay considerable penalties for that controllability. A negative exponent cored charge with a controlled area nozzle could give thrust control over the limited range required. A turn-down ratio of 2 would be quite satisfactory, while a response time of 1/100th of the burn time is achievable and would probably be more than satisfactory for height control. High specific impulse in the bulk propellant would be a large gain in a vehicle where the thrust is required to support the weight.

Lastly, a controlled thrust rocket motor could in theory replace many of the boost-sustain and pulsed-boost motors presently in use. For these applications, turn-down ratios of up to about 5 would be required, and these are not yet available. Further research into negative exponent propellants is needed before this use could be seriously addressed. Response time is not very important, but high specific impulse and low signature in the bulk propellant are high priorities.

7. CONCLUSION

A method of designing an end-burning solid propellant rocket motor charge with a large negative effective pressure exponent has been presented. The charge design incorporates fibres or strands of core material embedded in the matrix of the bulk propellant and aligned generally perpendicular to the intended burning face. The cross sectional area of the cores can be very small compared to the overall burning surface area, so that the mean combustion gas properties are essentially those of the bulk propellant. Cone burning is forced around each core by arranging that the core material over the operating pressure range of the motor has a higher burning rate than that of the bulk material. Thus the core regresses faster than the bulk propellant, exposing extra surface area in the bulk propellant in the form of a cone around the core, until the cones from adjacent cores intersect. This quasi-steady-state surface, consisting of a large number of intersecting cones, now regresses at a linear rate equal to the core burn rate. The bulk propellant is consumed at exactly the same rate as if the original planar surface had regressed at the core burn rate. In other words, the charge produces a gas whose properties are those of the bulk propellant, at the mass flow rate of a charge made of the core propellant. As the core propellant has a negative pressure exponent, the entire charge produces gas at a rate which has a negative pressure exponent.

This method uses cores of negative exponent propellant embedded longitudinally in a charge of conventional propellant. This method of charge design has the significant advantage that it separates the problems of charge design into three independent areas.

(i) A negative exponent core propellant material, which provides the negative exponent property to the whole charge. Several examples of such propellants have been presented.

(ii) A burning rate amplification method, which increases the burning rate of the core propellant material to give any desired core burning rate, without affecting the negative exponent. Possible methods of burning rate amplification have been proposed.

(iii) A bulk propellant, which can be chosen to give optimum properties for the application intended without affecting the charge burning rate or negative exponent.

The resultant charge has all the advantages of negative exponent charges produced entirely from negative exponent propellant, except for the almost instantaneous response of the completely homogeneous negative exponent charge. The negative exponent core charge can, however, be made with as small a response time as required, provided a sufficient number of closely spaced cores can be embedded in the charge. The cored charge has none of the major disadvantages of the homogeneous negative exponent charge, because the bulk propellant can be selected to give whatever performance is required.

8. ACKNOWLEDGEMENTS

The authors acknowledge the contribution of Mr N. Ayres and Mr S. Odgers of Nitrocellulose Propellants Group, WSRL, who drew our attention to the extreme pressure sensitivity of the EDB composition quoted above, and provided the propellant strands and charges used in this work.

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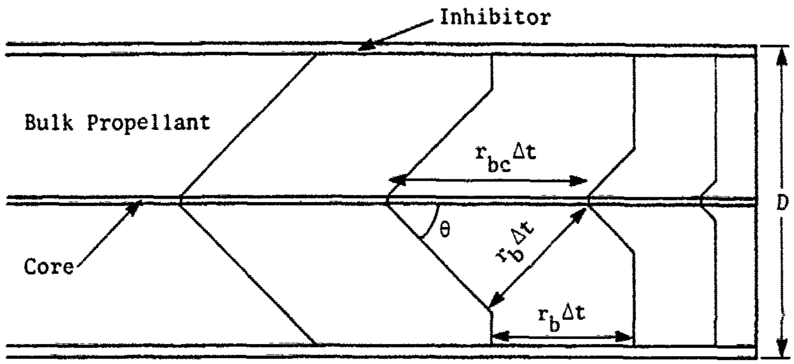

Figure 1. Single core charge, showing nomenclature and cone development

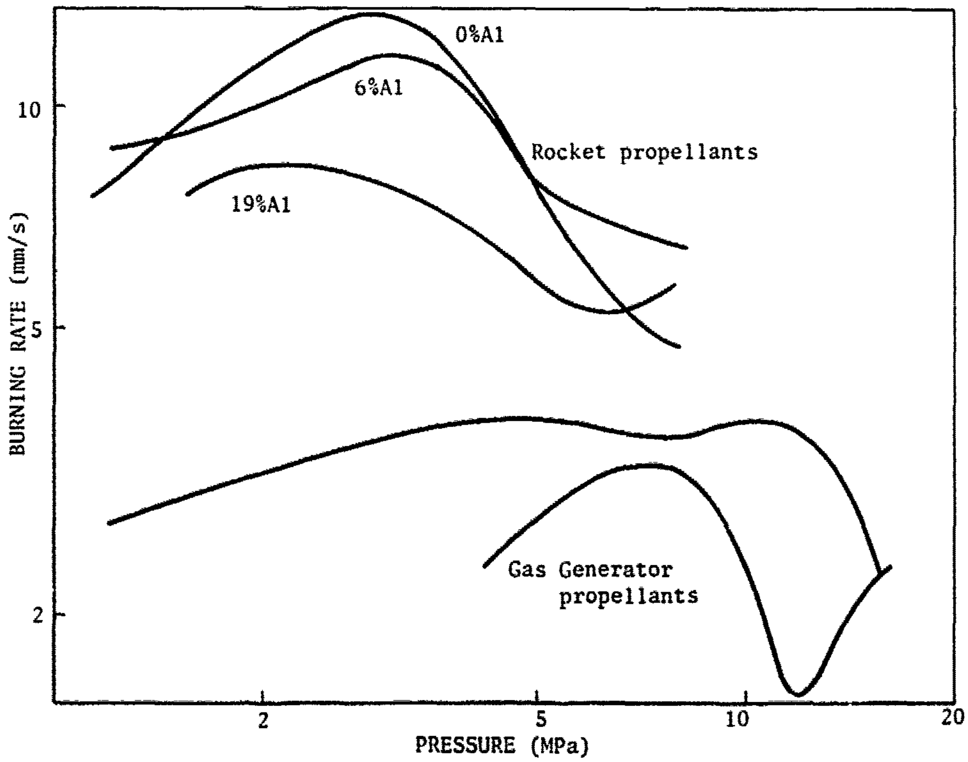

Figure 2. Typical negative exponent propellant r_b vs P (Cohen, Landers and Lou)

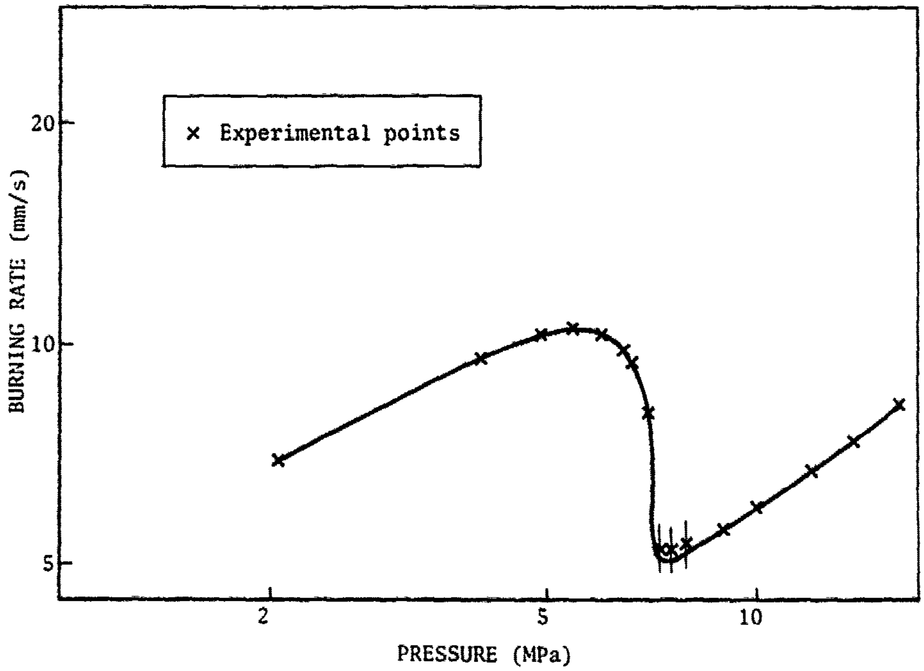

Figure 3. WSRL negative exponent EDB propellant r_b vs P

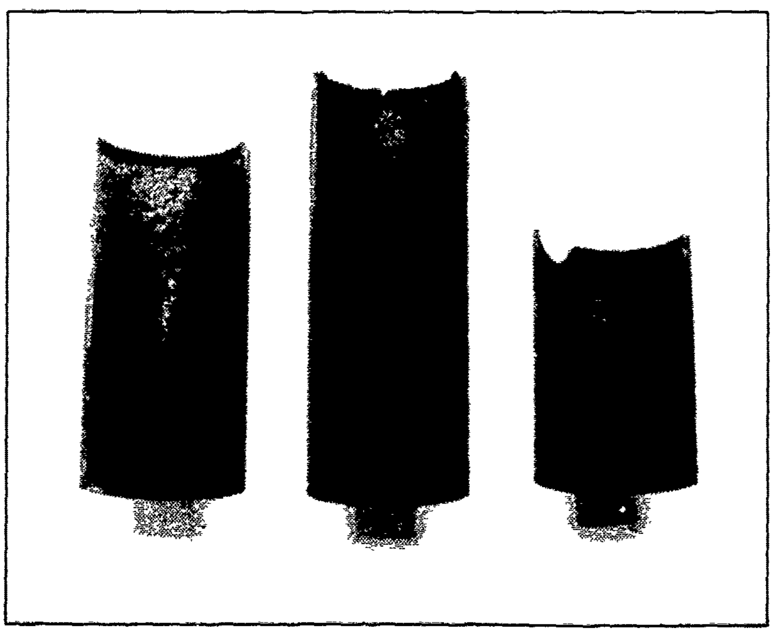

Figure 4. Sectioned view of single core charges after firing

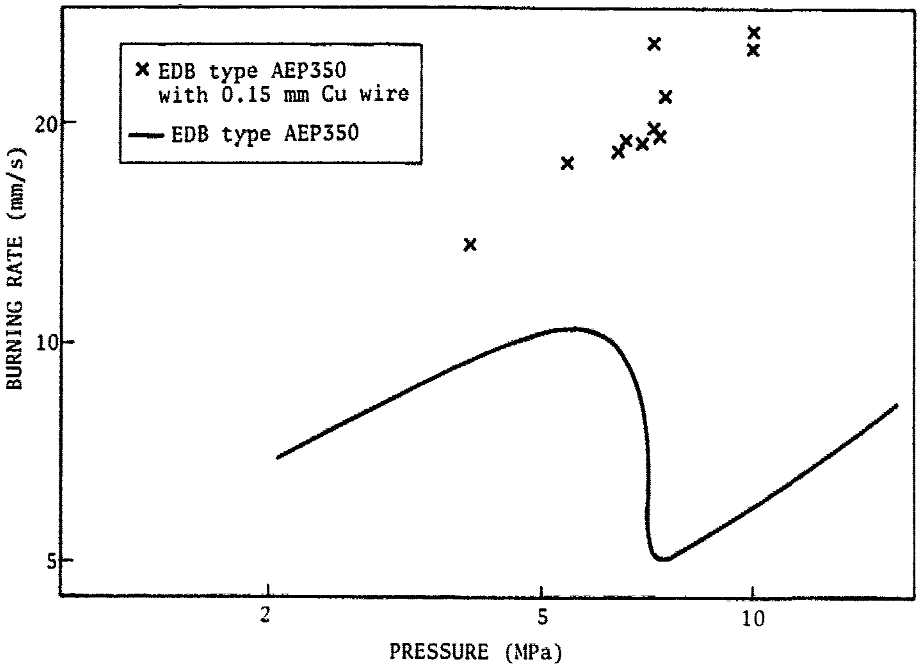

Figure 5. Effect of Cu wires on negative exponent EDB

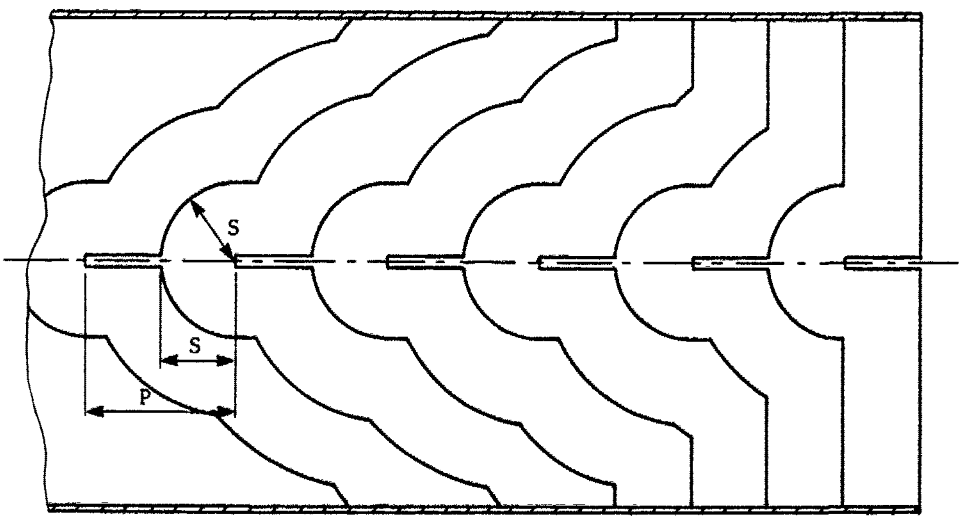

Figure 6. Development of burning surface to approximate conical surface by use of an axial line of spaced cavities (Bradfield)

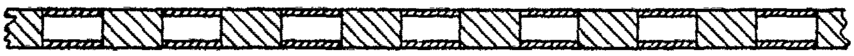

Figure 7. Negative exponent strand of Bradfield cavities

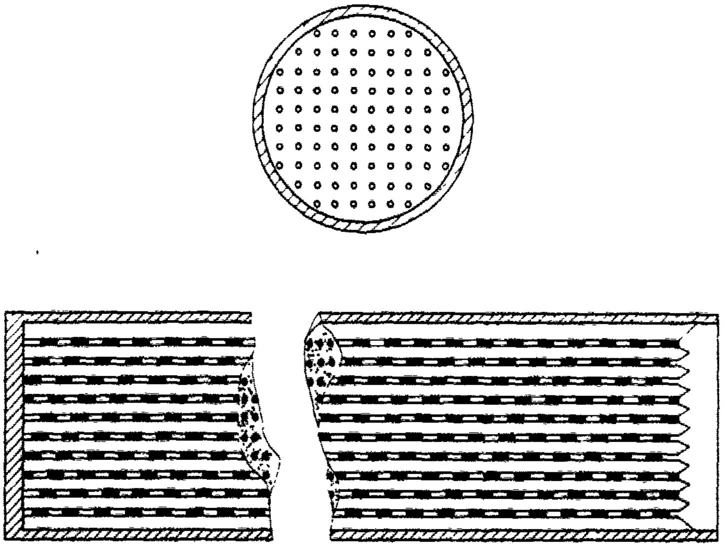

Figure 8. Negative exponent charge using strands of Bradfield cavities

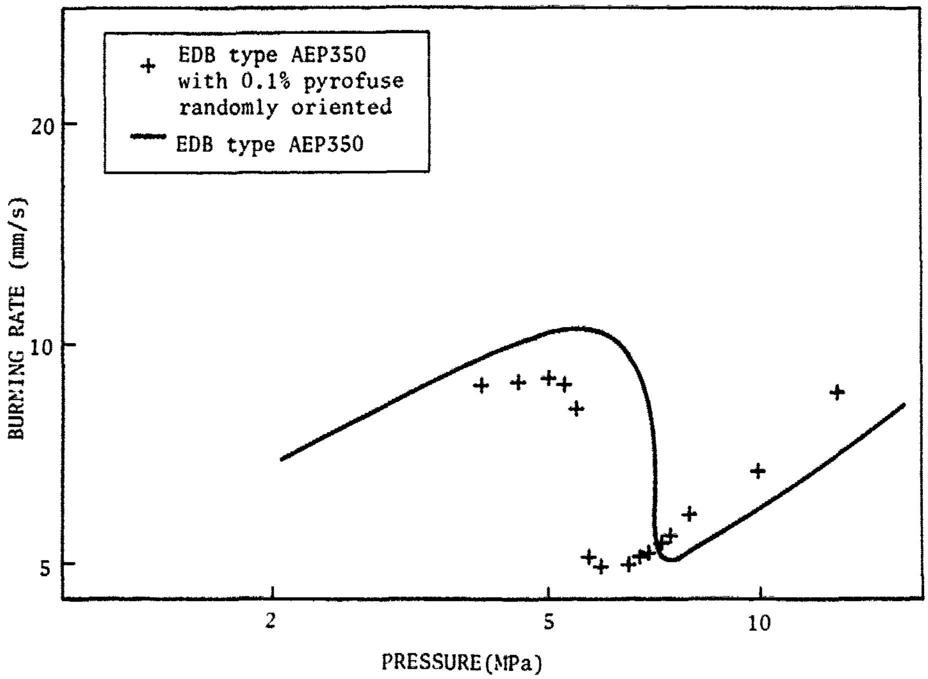

Figure 9. Effect of Pyrofuse on negative exponent EDB

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16 SUMMARY OR ABSTRACT:
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A novel method of making a solid propellant rocket motor or gas generator charge with a negative effective burning rate pressure exponent (negative dr_b/dP) is presented. The negative exponent characteristic can be obtained independently of burning rate and other bulk propellant properties (specific impulse, flame temperature, signature, mechanical properties, etc) which can be chosen as required.

The charge is constructed with a core, (or several cores), of propellant with an intrinsically negative pressure exponent with the bulk of the charge made up of any propellant with a lower burning rate than the core propellant over the pressure range of interest. The core propellant burning rate range can be adjusted to give the desired value by a method of burning rate acceleration.

Suitable core materials and burning rate acceleration methods are reported, and the use of such a charge in a rocket motor or gas generator with a variable area nozzle to give controllable thrust is discussed. (Keywords:

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